Tidal Interaction in High Mass X-ray Binaries and Symbiotic Stars

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(invited talk)

Abstract. This paper summarizes our recent results on tidal interaction in high mass X-ray binaries and symbiotic stars. We demonstrate that the giant in symbiotic stars with orbital periods ≤ 1200 d are co-rotating (synchronized). The symbiotics MWC 560 and CD-43^{0}14304 probably have high orbital eccentricity. The giants in symbiotic binaries rotate faster than the field giants, likely their rotation is accelerated by the tidal force of the white dwarf.

The giant/supergiant High mass X-ray binaries with orbital periods ≤ 40 d are synchronized. However the Be/X-ray binaries are not synchronized. In the Be/X-ray binaries the circumstellar disks are denser and smaller than those in isolated Be stars, probably truncated by the orbiting neutron star.

Key words: stars: rotation – binaries: spectroscopic – binaries: symbiotic – stars: emission-line, Be – stars: late type

Приливно взаимодействие в масивни рентгенови двойни и симбиотични звезди

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Тази статия представя резултатите от нашите изследвания на приливното взаимодействие в масивни рентгенови двойни и симбиотични звезди. Ние демонстрираме, че симбиотичните звезди, с орбитални периоди ≤ 1200 дни, са синхронизирани. Симбиотичните звезди MWC 560 и CD-43^{0}14304 вероятно имат орбити с голям ексцентрицитет. Гигантите в симбиотични се въртят по-бързо от гигантите от полето, вероятно тяхното въртене е ускорено от приливната сила на бялото джудже.

Масивните ретгенови двойни с гигант/свръхгигант и орбитални периоди ≤ 40 дни са синхронизирани. Be/рентгеновите двойни не са синхронизирани. В тях околозвездните дискове са по-плътни и по-малки от тези в изолираните звезди, вероятно отрязани от неутронната звезда.

1 Introduction

Stars in close binary systems are subject to mutual tidal forces that distort their stellar shape, breaking their spherical and axial symmetry, which leads to different observational effects – ellipsoidal variability and apsidal motion, circularization, transition period between circular and eccentric orbits, synchronization and spin-orbit alignment (e.g. Mazeh 2008). We investigate a few observational appearances of the tidal force of the compact object on the mass donating star in symbiotic stars (SSs) and High Mass X-ray Binaries (HMXrB).

The symbiotic stars (thought to comprise a white dwarf accreting from a cool giant or Mira) represent the extremum of the interacting binary star classification (e.g. Corradi et al. 2003). On the basis of their IR properties, SSs have been classified into stellar continuum (S) and dusty (D or D') types (Allen 1982). The D–type systems contain Mira variables as mass donors. The D'–type are characterized by an earlier spectral type (F-K) of the cool component and lower dust temperatures.

In HMXrB a neutron star or stellar mass black hole accretes material from a massive early type star. They are divided in two groups: (1) Be/X-ray binaries and (2) giant/supergiant systems.

The aims of our investigations are:

– to measure the projected rotational velocities ($v \sin i$) and the rotational periods (P_{rot}) of the giants in a number of southern symbiotic stars;

– to perform comparative analysis and explore theoretical predictions that the mass donors in symbiotics are faster rotators compared with field giants;

– to check whether the rotation of the red giants in SSs is synchronized with the orbital period;

– to check whether the rotation of the mass donors in HMXrB is synchronized with the orbital period.

2   Observations

We have observed 42 symbiotic stars – all southern S- and D'-SSs from the catalogue Belczyński et al. (2000) with $0^h < RA < 24^h$, declination $< 2^0$, and catalogue magnitude brighter than $V < 12.5$.

The observations have been performed with FEROS at the 2.2m telescope (ESO, La Silla). FEROS is a fibre-fed echelle spectrograph, providing a high resolution of $\lambda/\Delta\lambda =$48000, a wide wavelength coverage from about 4000 Å to 8900 Å in one exposure (Kaufer et al. 1999). All spectra are reduced using the dedicated FEROS data reduction software implemented in the ESO-MIDAS system. Using CCF and FWHM methods, we measured the projected rotational velocity ($v \sin i$) on our observations, and on spectra from the archives of VLT/UVES and ELODIE (Zamanov et al. 2008).

3   The mass donors in S–type symbiotics are co-rotating

From our $v \sin i$ measurments and data collected from the literature, we calculate P_{rot} (rotational period of the giant):

$$P_{rot} = \frac{2\pi R_g \sin i}{v \, \sin i}, \tag{1}$$

where R_g is the radius of the mass donor, i is the inclination of the orbit to the line of sight. In the most cases for R_g, we use the the average radius for the corresponding spectral type taken from van Belle et al.(1999).

We collected 18 S-type SSs in total, for which we know the orbital period (P_{orb}) and P_{rot}. Fig. 1 shows P_{rot} versus P_{orb} of the 18 objects in our sample, with a straight line indicating the co-rotation (i.e. $P_{rot}=P_{orb}$). Most objects are close to this line, which suggests that they are synchronized. 9 objects are synchronized within the measurement errors (1-σ level). 4 objects have deviations between 1 and 2-σ. Generally, 15 out of 18 are within the 3-σ level.

The objects that deviate significantly from the $P_{orb}=P_{rot}$ line are RS Oph, MWC 560 (peculiar symbiotics), and CD-43°14304.

In Fig. 1 figure, it is visible that the symbiotic stars with $P_{orb} < 1200$ days are synchronized (Zamanov et al. 2007). The statistical tests demonstrate
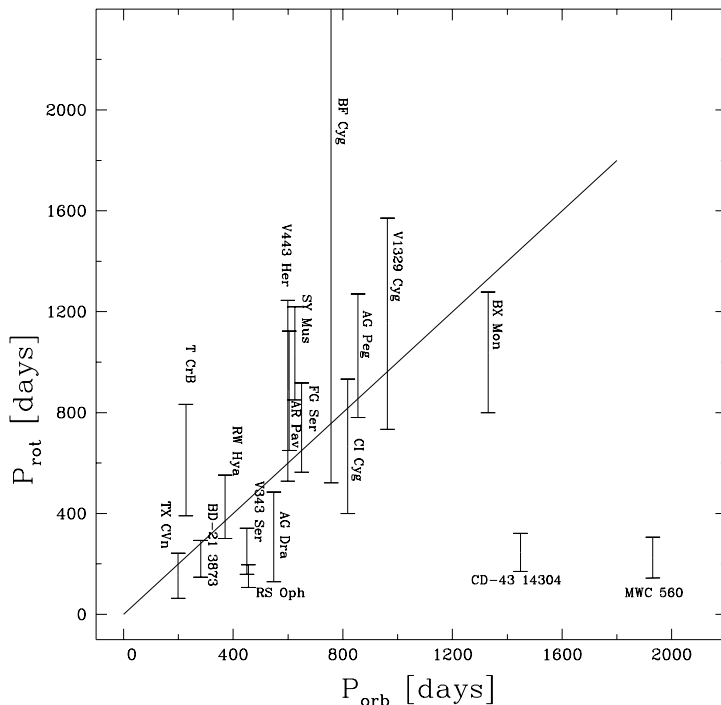
Fig. 1. The rotational period of the red giant (P_{rot}) versus the orbital period (P_{orb}) for S-type symbiotics. The solid line corresponds to $P_{rot} = P_{orb}$. Most objects are close to this line, which indicates that they are synchronized. There are 3 objects which deviate considerably from that rule (RS Oph, CD-43°14304, MWC 560).

that the deviations are (most probably) due to measurement errors and not to intrinsic scatter. In other words the null hypothesis that all S-type SSs with well measured $v \sin i$ are synchronized (excluding RS Oph, CD-43°14304, MWC 560) cannot be rejected at the 99% confidence level.

4 Orbit eccentricity of MWC 560 and CD-43^{0}14304

MWC 560 (V694 Mon) is a symbiotic binary system, which consists of a red giant and a white dwarf (Michalitsianos et al. 1993). The most spectacular features of this object are the collimated ejections of matter with velocities of up to ~ 6000 km s^{-1} (Tomov et al. 1992; Stute & Sahai 2009) and the resemblance of its emission line spectrum to that of the low-redshift quasars. The jet ejections are along the line of sight and the system is seen almost pole-on ($i < 16°$).

In a binary with a circular orbit the rotational period of the primary, P_{rot}, reaches an equilibrium value at the orbital period, $P_{rot} = P_{orb}$. However, in a binary with an eccentric orbit, the tidal force acts to synchronize the rotation of the mass donor with the motion of the compact object at the periastron –

the effect called pseudosynchronous rotation (Hall 1986). The corresponding equilibrium (i.e. pseudosynchronization) is reached at a value of $P_{\rm rot}$ which is *less* than $P_{\rm orb}$, the amount less being a function of the orbital eccentricity e. Hut (1981) showed that the period of pseudosynchronization, $P_{\rm ps}$, is :

$$P_{\rm ps} = \frac{(1 + 3e^2 + \frac{3}{8}e^4)(1 - e^2)^{\frac{3}{2}}}{1 + \frac{15}{2}e^2 + \frac{45}{8}e^4 + \frac{5}{16}e^6}P_{\rm orb}. \tag{2}$$

For MWC 560, we measured $v \sin i = 8.2 \pm 1.0$ km s^{-1}. Following Schmid et al. (2001), we adopt red giant radius $R_{\rm g} = 140 \pm 7\ R_\odot$, and inclination $i = 12° - 16°$. We calculate $P_{\rm rot} = 155 - 270$ days. This value is considerably less than the orbital period, $P_{\rm orb} = 1931 \pm 162$ days ($P_{\rm orb}$ from Gromadzki et al. 2007). Following the estimations of the timescales (Stoyanov 2010), MWC 560 should be close to synchronization or pseudosynchronization, and $P_{\rm rot} = P_{\rm ps}$. Using Eq. 2 we can therefore estimate the orbital eccentricity to be $e = 0.73 - 0.79$.

CD-43^{0}14304 : It is a symbiotic star with mass donor K5III and a white dwarf with temperature T=110 000 K. We assume $P_{\rm orb} = 1448 \pm 100$ days (Schmid et al., 1998) and red giant radius $R_{\rm g} = 38.8 \pm 2\ R_\odot$. Spectropolarimetry (Harries & Howarth 2000) gives two possible values for the inclination of the system $i = 57^0 \pm 5^0$ or $i = 122^0 \pm 48^0$. Both values imply $\sin i \approx 0.84$. We calculate $P_{\rm rot} \approx 170 - 321$ d and e (using Eq. 2). It is likely that the eccentricity is high $e = 0.61 - 0.76$.

4.1 D'-type symbiotics

There are 7 D' SSs listed in the catalogue of Belczyński et al. (2000). Rotational velocities are measured for all six southern objects. They are summarized in Table 1. $v \sin i$ of V471 Per is unknown, but it will be valuable to measure it.

Table 1. D'-type symbiotics. In the table are gives as follows: name of the object, spectral type of the mass donor, $v \sin i$ (our measurement), $v \sin i$ of field giants with identical spectral type, adopted radius of the giant (R_g), critical velocity, the ratio $\frac{v \sin i}{v_{\rm crit}}$.

Object	IR type	Spec	$v \sin i$ [km s^{-1}]	similar objects $v \sin i$ [km s^{-1}]	R_g [R$_\odot$]	v_{crit} [km s^{-1}]	$\frac{v \sin i}{v_{\rm crit}}$
WRAY 15-157	D'	G5III	37±5.0	< 15	10.0	198	0.19
HD 330036	D'	F8III	107.0±10	10-35	22.1	160	**0.67**
Hen 3-1591	D'	K1III	23.7±2.0	1-41	23.9	144	0.16
StHα 190	D'	G4III/IV	105.0±10	< 24	7.88	191	**0.54**
V417 Cen	D'	G9Ib-II	75.0±7.5	1-20	75.0	105	**0.71**
AS 201	D'	F9III	29.3±3.0	10-35	24.5	150	0.19
V471 Per	D'	G5III	?	< 15	10.0	198	–
Hen 3-1674	S	M5III	52.0±6	< 20	139.6	60	0.8 ?

WRAY 15-157: The catalogue of rotational velocities for evolved stars (de Medeiros & Mayor 1999) lists 18 objects from spectral type G5III. They all rotate with $v \sin i < 15$ km s^{-1}. WRAY 15-157 with $v \sin i = 37 \pm 5$ km s^{-1}, is an extremely fast rotator for this spectral class.

Hen 3-1591 The same catalogue lists >60 K1III stars, and 90% of them rotate with $v \sin i < 8$ km s^{-1}. There are only 5 with $v \sin i > 20$ km s^{-1}. This means that Hen 3-1591 is a very fast rotator (in the top 5%).

AS 201, HD 330036: The same catalog contains 5 objects from spectral type F8III-F9III. They rotate with $v \sin i$ of 10-35 km s^{-1}. AS 201 is well within in this range. However HD 330036 is an extremely fast rotator. The same catalog lists 60 objects from spectral type G3,G4,G5 III-IV. They all rotate with $v \sin i < 24$ km s^{-1}. Again, this means that StHα 190 is an extremely fast rotator.

V417 Cen: The catalog of de Medeiros et al. (2002) of $v \sin i$ of Ib supergiant stars contains 16 objects from spectral type G8-K0 Ib-II. All they have $v \sin i$ in the range 1-20 km s^{-1}. It means that V417 Cen is an extreme case of very fast rotation for this spectral class.

V471 Per: $v \sin i$ of V471 Per is unknown, but it will be valuable to measure it.

Hen 3-1674 is classified as S-type, however its rotation is similar to that of D'-SSs. an independent check of the parameters will be valuable.

There is a natural upper limit for rotation speeds, where the centripetal acceleration balances that due to gravitational attraction, often named the "critical speed", where $v_{\mathrm{crit}} = \sqrt{GM/1.5R} = 357\sqrt{M/R}$ km s^{-1} (the factor of 1.5 appears from the assumption that at critical rotation speeds the equatorial radius is 1.5 times the polar radius, R). The calculated v_{crit} is included in Table 1. No star can rotate faster than its critical speed, however we can see that at least three D'–type SSs are rotating at a substantial fraction of their critical speeds. For the remaining objects we can not exclude the possibility that they also rotate very fast but are observed at low inclination ($i \leq 30^0$).

All mass donors in D'–type systems appeared to be very fast rotators (see also Pereira et al. 2005; Zamanov et al. 2006). Four of them are the fastest rotators in their spectral class.

As an after effect of the fast rotation D'-SS should be flattened at the poles and bulging at the equator. The mass loss rate must be enhanced in equatorial regions, this will create dense circumstellar disk. In the outer parts of the disk there should be conditions for formation of dust. Consequently the appearance of the dust in these systems is (probably) a direct consequence of their fast rotation.

If these binary stars are synchronized, their orbital periods should be relatively short (4-60 days).

5   Fast rotation in S-type symbiotics

Soker (2002) has predicted theoretically that the cool companions in symbiotic systems are likely to rotate much faster than isolated cool giants or those in wide binary systems. Our observational investigation (Zamanov et al. 2006, 2008) clearly confirms theoretical predictions that the mass donors in symbiotics are fast rotators.

Table 2. Projected rotational velocities of K and M giants. In the table are given as follows: the spectral type, the mean projected rotational velocity ($v \sin i$, in $\mathrm{km\,s^{-1}}$), standard deviation of the mean (σ, in $\mathrm{km\,s^{-1}}$), the number of objects. In the second column are given the values for the field M giants, in the third - for the symbiotic stars.

Spectral bin	field giants mean $v \sin i \pm \sigma$ [$\mathrm{km\,s^{-1}}$]	N	symbiotics mean$\pm\sigma$ [$\mathrm{km\,s^{-1}}$]	N
K2-K5 III	1.1±1.4	(363)	9.5±6.7	(7)
M0-M1 III	3.7±1.9	(23)	9.9±2.6	(2)
M1.5-M2 III	4.8±4.1	(14)	8.3±1.1	(3)
M2.5-M3 III	5.5±2.0	(8)	6.5±1.8	(4)
M3.5-M4 III	2.2±1.0	(3)	7.7±3.3	(7)
M4.5-M5 III	5.5±4.0	(5)	7.9±1.7	(9)
M5.5-M6 III	12.1±5.1	(4)	7.6±2.0	(6)

The mean values of $v \sin i$ for the K and M giants are presented in Table 2. All but one of the mean $v \sin i$ values of SSs are higher than those of the field giants.

The K giants in S-type symbiotics rotate at $v \sin i > 4.5$ $\mathrm{km\,s^{-1}}$, which is 2– 4 times faster than the field K giants. The majority of the field M giants rotate at about $v \sin i \sim 1 - 6$ $\mathrm{km\,s^{-1}}$, while the symbiotic M giants rotate at $v \sin i \sim 4 - 14$ $\mathrm{km\,s^{-1}}$. The M giants in S-type symbiotics rotate on average 1.5 times faster than the field M giants.

A few histrograms comparing symbiotics and field giants can be seen in Zamanov et al. (2008). Statistical tests (Kolmogorov-Smirmov and Mann-Whitney U-test) show that these differences are highly significant – p-value $< 10^{-3}$ in the spectral type bins K2III-K5III, M0III-M6III, and M2III-M5III;

6 High mass X-ray binaries

6.1 Synchronization

We investigate the tidal interaction in High-Mass X-ray Binary stars in order to determine in which objects the rotation of the mass donors is synchronized or pseudosynchronized with the orbital motion of the compact companion. We calculate the rotation (P_{rot}) of the mass donor and compare it with the orbital period (P_{orb}). The results for 12 HMXrB with known orbital and stellar parameters are plotted in Fig.2 (see also Stoyanov & Zamanov 2009)

We find that: **(1)** the Be/X-ray binaries are not synchronized, the mass donors rotate faster than the orbital period; **(2)** the giant and supergiant systems are close to synchronization (at least for systems with orbital periods $\mathrm{P}_{orb} < 40$ days). The only exception is 1A 0535+262 (V725 Tau). This object in its observational behaviour is more similar to the Be/X-ray binaries (e.g.
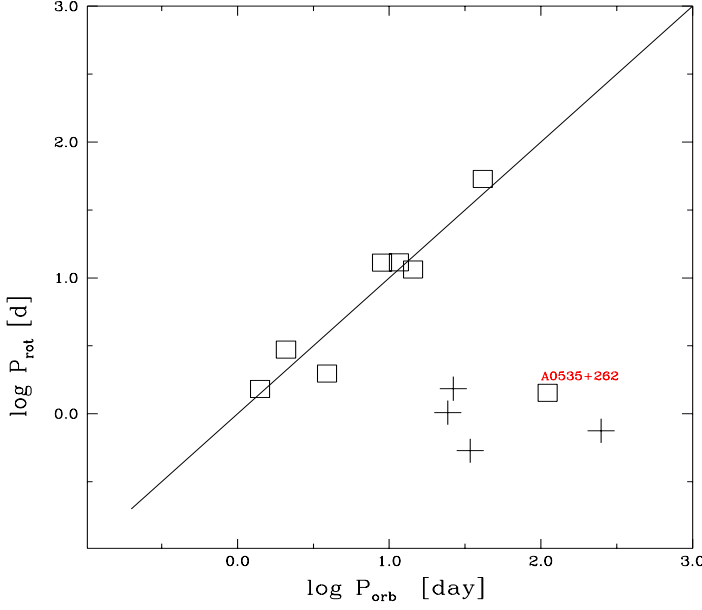
Fig. 2. The rotational period of the mass donor (P_{rot}) versus the orbital period (P_{orb}) for 12 HMXrB. The solid line corresponds to $P_{rot} = P_{orb}$. The squares are giant and supergiant systems, the crosses - Be/X-ray binaries. The giants/supergiants are close to the line of synchronization. The Be/X-ray binaries are not synchronized. Typical errors are of the size of the symbols.
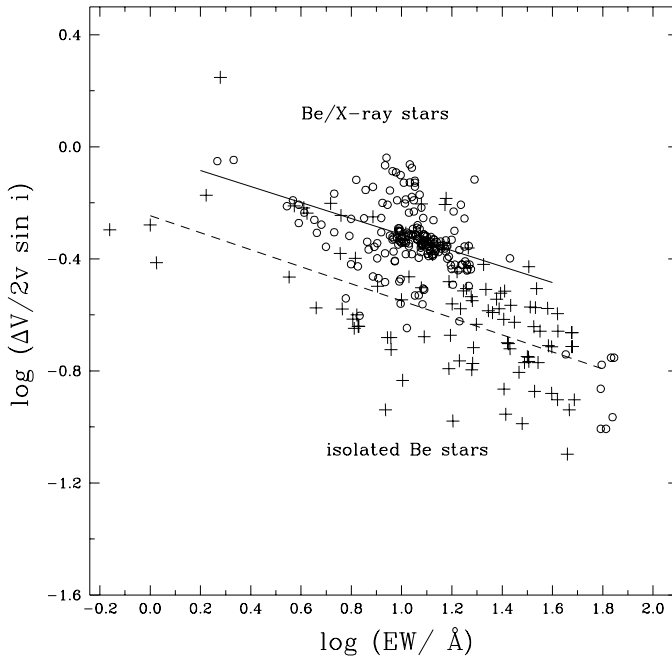
Fig. 3. Plot of Hα line parameter $\log\left(\Delta V/(2\,v\sin i)\right)$ versus EW(Hα). The lines represent the best linear fits: the solid line over the circles (Be stars), the dashed line over the crosses (Be/X-ray stars). The best fit line of the Be/X-ray binaries is shifted to denser circumstellar disks. Our estimation is that the circumstellar disks in the Be/X-ray systems are about $\simeq 2$ times more dense than disks in isolated Be stars.

Coe et al. 2006), and our result gives clue that the physical reason is the rotation of the mass donor.

6.2   Comparison of the circumstellar disks in Be/X-ray binaries and Be stars

We performed a comparative study of the circumstellar disks in Be/X-ray binaries and isolated Be stars based upon the Hα emission line (Zamanov et al. 2001). From this comparison it follows that the overall structure of the disks in the Be/X-ray binaries is similar to the disks of other Be stars, i.e. they are axisymmetric and rotationally supported. The factors for the line broadening (rotation and temperature) in the disks of the Be stars and the Be/X-ray binaries seem to be identical.

However, we do detect some intriguing differences between the envelopes. On average, the disks in Be/X-ray binaries have on average a smaller size, probably truncated by the compact object. The different distribution of the Be/X-ray binaries and the Be stars seen in the normalized peak separation versus equivalent width of $H\alpha$ diagram (see Fig. 3) indicates that the circum-

stellar disks of the Be/X-ray binaries are twice as dense as the disks of the isolated Be stars.

7   Conclusions

Our main results are as follows:

The giants in S- and D'-type symbiotic stars are fast rotators in comparison with field giants. At least three of the D'-symbiotic stars rotate at a substantial fraction of the critical velocity. If D'-symbiotics are tidally synchronized, their orbital periods could be surprisingly short (5-50 d).

In the symbiotic stars with $P_{orb} < 1200$ d, the rotation of the red giant is tidally locked with the orbital motion. Assuming pseudosynchronization, we calculate that the orbital eccentricities of MWC 560 and CD-43^{0}14304 can be surprisingly large ($e \gtrsim 0.6$).

In HMXrB, the rotation of the giants/supergiants is tidally synchronized for systems with for systems with P_{orb} shorter than 42 d.

Nor the rotation of the Be stars in Be/X-ray binaries, nor the formation of the circumstellar disk is influenced by the neutron star. However the circumstellar disks are truncated, in other words the influence of the neutron is detected in the outer part of the circumstellar disks.

Open questions, which should be addressed in the future:
- what is the reason for the extremely fast rotation of D'-symbiotics?
- what is the case of Hen 3-1674?
- are the symbiotics with $P_{orb} > 1200$ d synchronized?
- are the supergiants in HMXrB with $P_{orb} > 40$ d synchronized?

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